MAGNETIC PARTICLE INSPECTION SIMULATION MODEL

Atul Athavale, Lalita Udpa, Satish Udpa, Zuorong Zhang
Department Of Electrical and Computer Engineering
Iowa State University
Ames, IA-50011

INTRODUCTION

The Magnetic Particle Inspection (MPI) method is generally used to detect surface and near surface flaws. In a MPI test, a ferromagnetic specimen in unmagnetized state is sprayed with magnetic particles in an aerosol suspension. The particles are generally ferromagnetic oxides coated with fluorescent pigments and the suspension is a petroleum distillate of low viscosity. The specimen is then magnetized. In the presence of a flaw transverse to the direction of the applied magnetic field, leakage fields are established on the surface of the specimen. These fields exert a translational force on the ferromagnetic particles in addition to a rotational torque. These two in combination accelerate the particles toward the flaw increasing the density of particles in the vicinity of the flaw. When excited by ultraviolet light, the particles emit visible radiation indicating the location of the flaw. This paper attempts to model the physical principles underlying the MPI method including imaging techniques to recreate the dynamics of the particles prior to their reaching an equilibrium around the flaw. The proposed approach has the capability to predict the time to equilibrium of the magnetic particles and the efficiency of the method in terms of the fraction of the total number of particles in the MPI image.

THE SIMULATION MODEL

The overall schematic of the simulation model is summarized in Figure 1. The three major components of this model are described below :

1. Statistical Model : The particles are sprayed on the surface of the specimen and allowed to come to a state of equilibrium before the specimen is magnetized. The residual magnetism of the test specimen is assumed to be zero. The initial

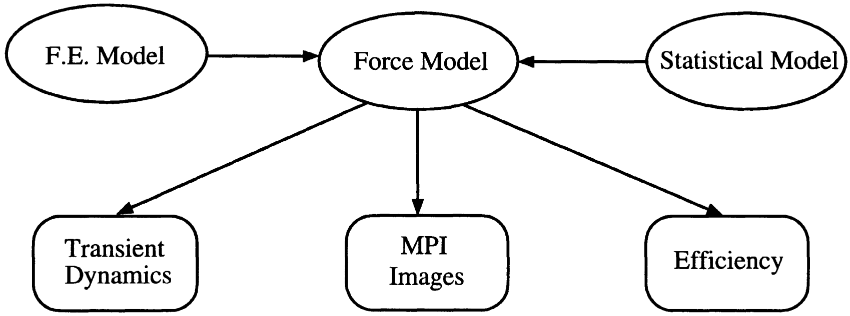


Fig 1 : The overall simulation model.

distribution of the magnetic particles is simulated by a statistical model. The random variable which is the position of the particle is assumed to have a uniform distribution. This assumption is valid as the surface area of the specimen under consideration is reasonably small. The probability density function 'p' of the position (x,y) is given by equation (1).

$$p(x, y) = \frac{1}{Area\ of\ inspection} \quad . \qquad (1)$$

The surface area is discretized by a Finite Element mesh into pixels and particles are assigned to the pixels using equation (1). Further processing is then carried out using the pixels rather than the particles themselves.

2. Finite Element Model : The leakage fields generated on the surface of the specimen are obtained using Finite Element analysis. The scalar potential formulation solves the governing equation of the form

$$\nabla^2 u = 0 \quad . \qquad (2)$$

The corresponding energy functional is of the form

$$Energy\ Functional = \int_{\Omega} \nabla u \cdot \nabla u \, dv \quad . \qquad (3)$$

3. The Force Model : The modeling of the forces on the magnetic particles is a key issue in the calculation of particle dynamics. The following simplifying assumptions are made.

1. The test specimen is initially unmagnetized.

2. The rotational torque is a transient with a very small time constant as compared to the translational force and is therefore ignored.

3. The effects of inertial, inter-particle and viscous forces are negligible as compared to the translational magnetic forces.

For a single pole of strength 'p' (Ampere-meter) the translational force in a magnetic field 'H' (Ampere/meter) is given by equation (4)

$$\overline{F} = \mu_0 p \overline{H} \qquad \text{(Newtons)} \ , \qquad (4)$$

where μ_0 (Henry/meter) is the permeability of free space.

Therefore, for a dipole with a separation 'd' (meter) the net force is given as

$$\overline{F} = \mu_0 p \overline{H_1} + \mu_0 (-p) \overline{H_2} \quad \text{(Newtons)} \qquad (5)$$

$$\overline{F} = \mu_0 p (\overline{H_1} - \overline{H_2}) \qquad \text{(Newtons)} \ , \quad (6)$$

where H_1 and H_2 are the field strengths at the two poles.

The relation for the magnetic moment 'm' is given by equation (7)

$$m = p \cdot d \ \text{(Ampere-sq. meter)} \ . \quad (7)$$

Substituting equation (7) in equation (6) we obtain

$$\overline{F} = \mu_0 m \frac{(\overline{H_1} - \overline{H_2})}{d} \qquad \text{(Newtons)} \ . \quad (8)$$

In the limiting case when 'd' tends to zero, this equation becomes

$$\overline{F} = \mu_0 m \frac{\partial \overline{H}}{\partial d} \qquad \text{(Newtons)} \ . \quad (9)$$

From equation (9) we conclude that the force on the magnetic particles is proportional to the magnetic moment and the gradient of the magnetic field rather than the field itself. Hence particles near the edge of the specimen experience a force which tends to drive them towards the edge rather than towards the flaw. This results in a loss of magnetic particles giving rise to the concept of efficiency. The efficiency can be defined as the fraction (N_{im}) of the total number of magnetic particles (N_{tot}) that form the MPI image.

$$\mathit{Efficiency} = \frac{N_{im}}{N_{tot}} \times 100 \ . \qquad (10)$$

Equation (9) can be used to calculate the acceleration 'a' and the displacement 's' of the particles by Newton's laws of motion as shown in equation (11) and (12).

$$\overline{F} = m \cdot \overline{a} \qquad \text{(Newtons)} \qquad (11)$$

$$\bar{s} = \bar{u} \cdot t + \frac{1}{2} \cdot \bar{a} \cdot t^2 \qquad \text{(meters)} \quad , \qquad (12)$$

where 'u' (meters/second) is the initial velocity.

THE COMPUTER SIMULATION

Consider a ferromagnetic rectangular block of dimensions 10.16 cm. X 5.08 cm. X 2.54 cm. with a rectangular flaw at the center of the face in the plane y = 0. The dimensions of the flaw are 0.05 cm. X 1.27 cm. X 0.08 cm. The leakage fields are obtained using a finite element model with boundary conditions (B_r) of 1.4 Tesla on the faces of the specimen in the planes x = -5.08 cm. and x = 5.08 cm. as shown in Figure 2. The magnetization of the particles is assumed to be 1700000 Ampere/meter and their density is assumed to be 7970 kg/cu.meter.

The overall simulation procedure is summarized below:

1. The intensity per magnetic particle 'I_m' is known. Therefore the total number of particles is calculated from the required intensity 'I_r' as

$$\textit{Number of Particles} = \frac{I_r}{I_m} \qquad (13)$$

2. The particles distribution on the surface of the test specimen is generated.
3. The finite element model is solved to obtain the leakage fields B_x and B_z.
4. The forces on the magnetic particles F_x and F_z and the corresponding accelerations a_x and a_z are calculated.
5. For each pixel,the displacements of the magnetic particles are calculated until the following termination criteria are met:
   a. The particle reached the flaw.
   b. The particle migrated out of the region of interest.
6. The time of observation is selected.

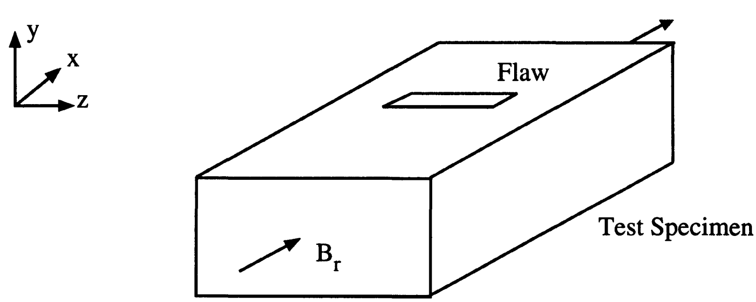


Fig 2 : The test specimen.

7. The corresponding position data of the magnetic particles is extracted from step (5). This information is then translated into particle density in each pixel to generate MPI images.

8. The efficiency of the method and the time to equilibrium of the magnetic particles are calculated.

The forces are symmetrical over the surface of the specimen. Hence the modeling needs to be done only over a quarter of the surface. The results are then mapped to the other quarters. This symmetry is apparent in the results generated.

RESULTS

The simulation results are shown below in the form of several plots and images. All units in the following figures are in meters.

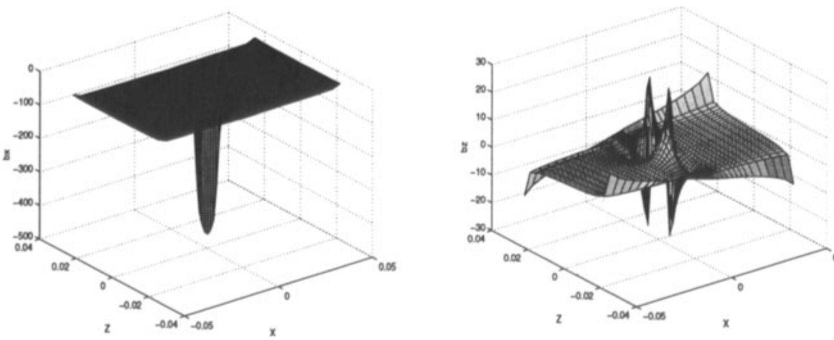
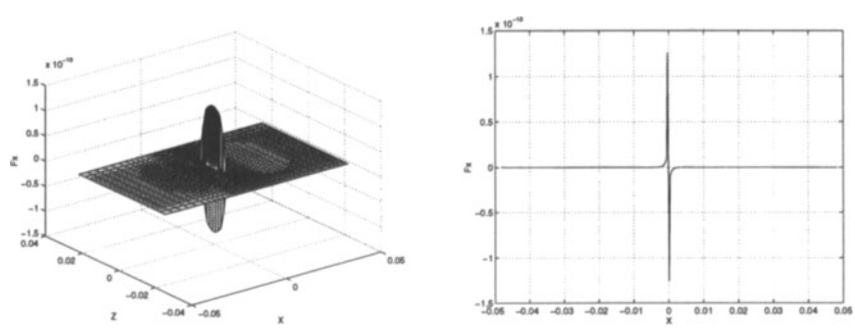
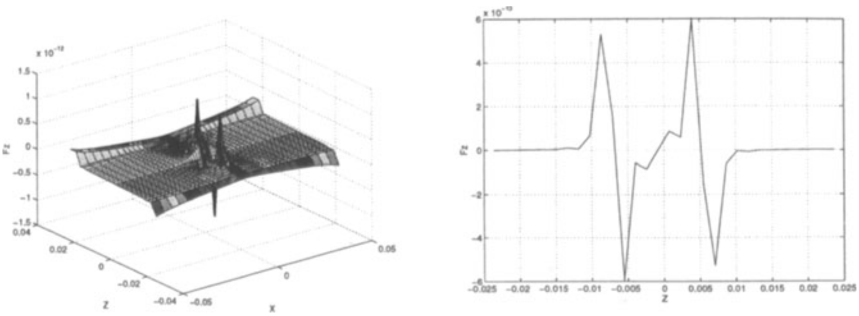


Fig 3 : Flux leakage components B_x and B_z from Finite Element Modeling [4].



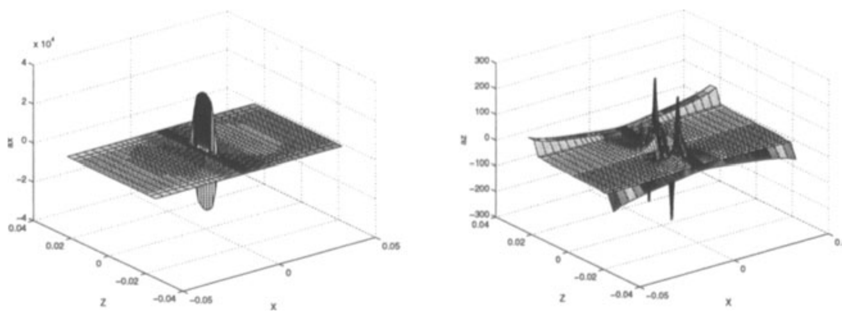
(a) (b)

Fig 4 : (a) Surface distribution and (b) Cross-section of F_x on the surface of the specimen.



(a) (b)

Fig 5 : (a) Surface distribution and (b) Cross-section of F_z on the surface of the specimen.



(a) (b)

Fig 6 : (a) a_x and (b) a_z on the surface of the specimen.

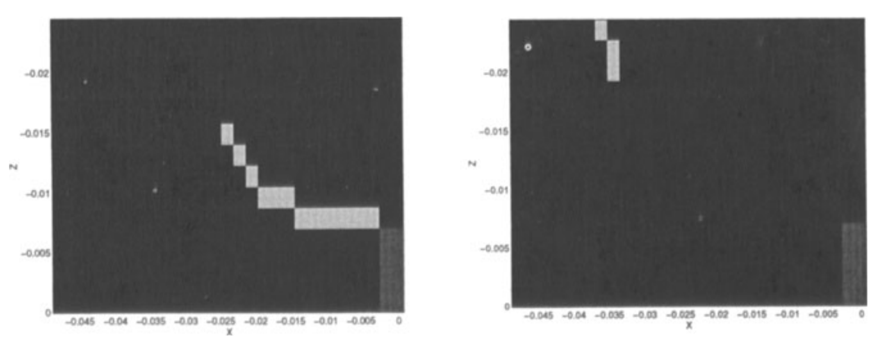


Fig 7 : Some paths of the magnetic particles simulated on a quarter of the surface.

The change in the particle distribution is displayed in the form of surface plots and gray level images at various observation times. The time intervals are selected to demonstrate the change in the particle densities in the gray level image as well as the surface plot.

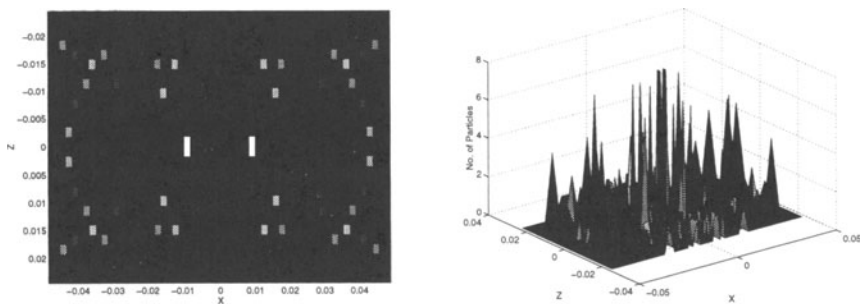


Fig 8 : The distribution of particles at t = 0 s with its gray level image.

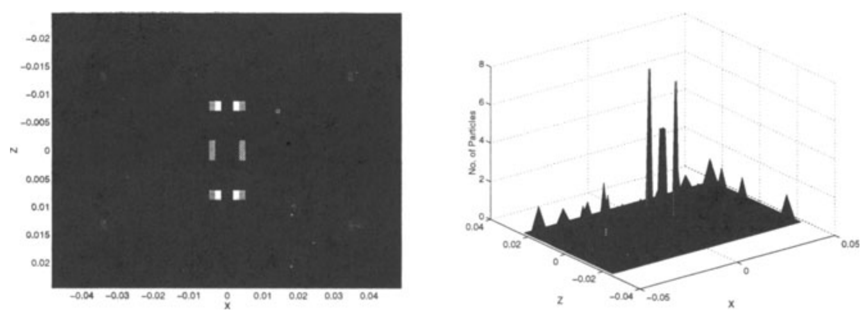


Fig 9 : The distribution of particles at t = 0.08 s with its gray level image.

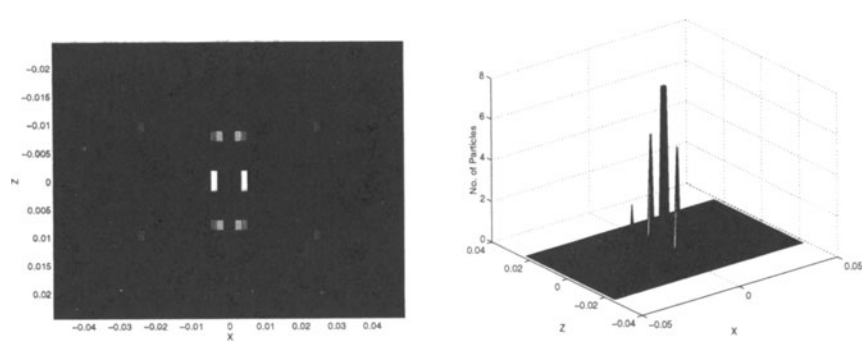


Fig 10 : The distribution of particles at t = 0.6 s with its gray level image.

CONCLUSION

It was found that for the given geometry and initial conditions, the particles reached dynamic equilibrium around the flaw in 0.6 seconds neglecting any inertial effects due to the mass of the particles. The efficiency of the method was found to be 59.5%. The model is simple, fast and reliable and gives an insight into the dynamic behavior of the particles. Most of the assumptions made are reasonable in the real world experimental conditions.

FUTURE WORK

This work could be extended to give a gamut of practically significant results. One suggested extension is the post-processing of the MPI images to improve recognition of the flaw. The model could also be used to optimize the experimental parameters in an in-service MPI testing. A forward transfer function could be obtained between the flaw dimensions and certain features of the MPI images. This could be used to obtain the solution of the inverse problem of identifying the flaw characteristics from a set of MPI images.

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